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Analysis of Scour Observations At Cantilever Outlets

Contents

Abstract

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This publication uses laboratory-developed procedures to analyze field data collected by the Soil Conservation Service (SCS) on scour holes at cantilevered pipe outlets and compares the field and laboratory findings. Data were compiled on discharge, pipe diameter and slope, soil classification and size, length of time the spillway flowed full, and dimensions of 105 scour holes surveyed in 17 States. Results of the analysis will aid SCS in predicting the sizes of scour holes and plunge pool energy dissipators at farm pond and flood-prevention cantilevered spillway exits.

KEYWORDS: scour hole, cantilever outlet, tailwater elevation, spillway, densimetric Froude number, culverts, jets, bed material.

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Analysis of Scour Observations at Cantilever Outlets

Fred W. Blaisdell[1]

Introduction

On September 10, 1962, D. A. Williams, administrator of the Soil Conservation Service (SCS), sent Advisory Notice W-705 to his State conservationists and heads of engineering and watershed planning units requesting field surveys and reports on the following:

1. All cantilever outlets with excessive scour;
2. At least five additional 24-in or larger cantilever outlets and associated scour holes, where the spillway had carried full pipe flow for at least five storms and the scour hole was stable or nearly so;
3. All cantilever outlets that had been repaired or modified to control the extent of scour.

After completing the study, SCS specialists sent the field survey data and reports to the St. Anthony Falls Hydraulic Laboratory of the Agricultural Research Service (ARS), Minneapolis, Minn., where a laboratory study was being made of scour at cantilever outlets. The SCS data could not be used, however, until ARS developed parameters that could be used to analyze the data. This publication reports that analysis.

Soil Conservation Service Field Data

Reports were received from 23 of the 50 States. No structures fell within the advisory notice criteria for six of the reporting States. Data were supplied by 17 States. The number of scour holes reported by each State varied from 1 to 16 and totaled 105. Of these 105 scour holes, 14 had pertinent data missing; 12 had such a high tailwater level that the jet floated and prevented calculation of the jet trajectory; 9 had been reshaped, repaired, or riprapped before the survey; and 7 had such a low flow that the cantilever pipe was only partly full.

For the 12 scour holes with a high tailwater level, the jet was computed assuming the pipe invert to be one diameter above the tailwater level. Data from the riprapped and repaired holes were plotted along with the other data. Where orifices restricted the outflow or the pipe was reported to be partly full, full flow was assumed for the computations. Despite these arbitrary assumptions, the data generally plot among the other data.

Data furnished for each structure were "as built" dimensions; as built and "as is" scour hole details regarding shape, size, depth, riprap, tailwater elevation, and photographs; discharge history of the principal spillway; and soil-boring logs and soil-classification tests. The quality of the data is highly variable. A good discharge history was particularly difficult to obtain for many spillways. The range of variables for the data used in this analysis is as follows:

1. Pipe diameter **D**: 15 to 42 in,
2. Discharge **Q**: 17 to 298 ft³/s,
3. Relative discharge $Q/(gD^5)^{1/2}$: 0.5 to 2.9,
4. Full flow time: up to 34 days,
5. Bed material size d_{50}:
   - 0.25 to 0.35 mm maximum for three holes,
   - 0.02 to 0.5 mm, mostly,
6. Bed material classification:
   - GW—well-graded gravel,
   - GM—silty gravel,
   - GC—clayey gravel,
   - SW—well-graded sand,
   - SP—poorly graded sand,
   - SM—silty sand,
   - SC—clayey sand,
   - ML—inorganic silt,
   - CL—inorganic clay of low to medium plasticity,
   - OL—organic silt,
   - CH—inorganic clay of high plasticity.

In addition to the requested data, four States submitted additional information as follows:

From Illinois:

Our *general* observations are as follows:

1. Duration of flow is a significant factor. Relatively small holes were observed on dams designed with little temporary storage and resultant short durations of flow. The larger holes exist below floodwater retarding dams.
2. The slope of the outlet channel is significant. If the flow can be conveyed immediately downstream without a "build-up" resulting in eddy currents, the hole tends to elongate and not have serious laterial erosion.
3. An underlying impermeable layer precludes the downward development of the basin, and encourages lateral dissipation of energy, resulting in large, shallow, scour holes.

From Indiana, R. H. Austin, State conservation engineer:

From my observations of scour holes formed by cantilever outlets, I have the following opinions:

1. That little or no damage occurs in soils which are fairly uniform in texture to a depth of 8–10 feet.
2. That where there is any significant change in the texture in a depth equal to at least four (4) times the diameter of the conduit below the outlet channel, that a scour hole be constructed to a depth of 8–10 feet.

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3. That when consolidated material is found in the depth as given in 2. above the scour hole be constructed not less than two (2) diameter of the conduit into the consolidated material even if the consolidated layer is 8-10 feet below the outlet channel. Consolidated material may be a clay pan to solid rock.
4. That the bottom width of the constructed scour hole be not less than three (3) times the diameter of the conduit and the length of the bottom be not less than four (4) times the diameter of the conduit.
5. That the bottom of the scour hole be so that the path of the jet from the conduit will be in the center of the bottom.
6. That a high tail water tends to cause excessive horizontal or lateral erosion around the scour hole.

From North Carolina:

The State conservation engineer and others have studied various stilling basins constructed to date within this state. They have arrived at the following conclusions.

Unless rock is encountered, the bottom width should be 20 feet with side slopes of 3:1 or 4:1. The bottom elevation for the stilling basin should be four to five feet below the elevation of the outlet channel. The length of this basin should be a minimum of 30 feet with pipes less than 30 inches in diameter and probably should be closer to a minimum of 50 feet for pipes of 30 inches in diameter or greater. One thing that would affect the length of the stilling basin would be the outlet channel. We also recognize that rock is an acceptable method for protection of the stilling basin. If the outlet channel has good grade and the water can get away from the stilling basin, less swirling action takes place. . . .

From Tennessee, R. F. Bratcher reported:

The scour holes appear to be in satisfactory condition and none appear to be in a condition which may cause a failure of the cantilever outlet or of the embankment.

Bratcher's analysis shows a correlation between the maximum width and depth of the scour hole and the plasticity index of the bed material. He concludes:

Conclusions. The results of this study indicate that the limiting scour depth and the volume of the scour hole are functions of three variables, (a) the discharge of the conduit, (b) the total head on the conduit, and (c) the soil properties, particularly the plasticity of the soil. These results are based on the findings and analyses of only fourteen scour holes in Tennessee, ...

Method of Analysis

The initial step in the analysis was to tabulate the cantilever pipe diameter and slope, the discharge and discharge history, soil data, and pertinent notes for each scour hole. The data are summarized in table 1. The scour hole dimensions were read from as built plans and as is profiles, cross sections and contour plots. Elevation data include the cantilever outlet invert elevation, the tailwater elevation for the full flow discharge, and the minimum elevation in the scour hole. Centerline station data include the cantilever outlet exit, the maximum scour, and the beginning and end of scour determined by projecting the upstream and downstream slopes of the scour hole to the tailwater elevation. The maximum width of the scour hole at the tailwater elevation was also recorded. Because laboratory studies had shown that the best defined scour hole lengths and widths were obtained by projecting the scour hole slopes to the tailwater elevation, this procedure was used when analyzing the field data.

The second step in the analysis was to express pertinent dimensions as dimensionless ratios. Most of these dimensions are defined in figure 1.

The discharge $\mathbf{Q}$ was converted to $\mathbf{Q}/(\mathbf{g}\mathbf{D}^5)^{1/2}$, where $\mathbf{g}$ is the gravitational acceleration and $\mathbf{D}$ is the conduit diameter. The distance of the cantilever invert above the tailwater level $\mathbf{Z}_p$ was converted to $\mathbf{Z}_p/\mathbf{D}$, the maximum depth of scour below the tailwater level $\mathbf{Z}_m$ to $\mathbf{Z}_m/\mathbf{D}$, and the distance from the cantilever exit to the maximum depth of scour $\mathbf{X}_m$ to $\mathbf{X}_m/\mathbf{D}$. The distance to the maximum scour depth was also expressed as $\mathbf{X}_m/\mathbf{X}_j$, where $\mathbf{X}_j$ is the horizontal distance from the cantilever pipe exit to the point where the free-falling jet centerline enters the tailwater plus the horizontal component of the tangent distance the jet travels between the tailwater and maximum scour elevations. The median diameter of the bed material $\mathbf{d}_{50}$ was converted to $\mathbf{d}_{50}/\mathbf{D}$. Laboratory studies had shown that because the nondimensional scour depth $\mathbf{Z}_m/\mathbf{D}$ is a function of the densimetric Froude number $\mathbf{F}_d = \mathbf{V}_p/[(-1 + \varrho_s/\varrho)\mathbf{g}\mathbf{d}_{50}]^{1/2}$, the densimetric Froude number was computed. Here $\mathbf{V}_p$ is the plunge velocity—the velocity at which the jet enters the tailwater, ϱ_s is the density of the bed material, and ϱ is the density of the fluid (water). The distances to the upstream end $\mathbf{X}_{b,tw}$, downstream end $\mathbf{X}_{e,tw}$, and center $\mathbf{X}_m$, and the maximum width $\mathbf{W}_{m,tw}$ of each scour hole at the tailwater elevation were nondimensionalized by the maximum scour depth $\mathbf{Z}_m$ to give $(\mathbf{X}_m - \mathbf{X}_{b,tw})/\mathbf{Z}_m$, $(\mathbf{X}_{e,tw} - \mathbf{X}_m)/\mathbf{Z}_m$, and $\mathbf{W}_{m,tw}/2\mathbf{Z}_m$. These data are summarized in table 2.

Table 1.—Summary of SCS Scour Hole Data

Hole number[1]	D feet	Q cfs	Time[2] days	S	Z_p feet	d_{50} mm	Unified Soil Classification	Notes
0101	2.00	50	30+21	---	+1.5	0.19-0.14	SM	Stable hole.
0301	1.83	50	324	---	-1.5	Riprap	----	Riprap repaired.
0901	2.00	50	13+	---	-0.4	0.1	OL, PI=6	Hole nearly stable. Photo shows rock.
0902	2.50	98	6	---	-0.2	0.2	SM, PI=0	Hole nearly stable.
0903	1.50	46	---	0.00268	+0.3	0.04-0.4	SM, PI=0, 38 mm	Hole nearly stable.
0904	2.00	8 o	---	---	+2.38	0.1-0.2	SM	Hole nearly stable. Orifice flow control.
0905	2.00	51	14	---	+0.9	0.4	SP, SM	Excessive scour. Rock placed on side slopes.
0906	2.50	75	---	---	+0.2	0.5	SP, SM	Excessive scour. Large rock placed upstream of bent.
0907	1.75	30	---	---	+1.85	0.2-0.6	SM, 12 mm max.	Excessive scour.
0908	3.50	52 o	8	---	-0.8	0.05	ML, PI=5, 2 mm	Excessive scour. Orifice flow control. Limestone bottom.
0909	2.50	25 o	2	---	+1.0	0.3	SM	Excessive scour. Orifice flow control.
0910	1.67	34	---	---	+1.0	0.2	SM	Excessive scour. Soil too tight to cut a sample.
0911	1.67	34	33	---	+1.7	0.05	ML, CL, PI 8-12	Excessive scour. Gravel shows in photo.
0912	2.00	50	32	---	+1.8	0.4	SM, ML	Excessive scour.
0913	2.00	50	22	---	-2.5	----	SM, ML, PI=4	Excessive scour. High tailwater. Soil too tight to sample.
0914	2.50	66	9	---	+0.5	----	SM	Nearly stable. Banks caving.
1101	2.00	66.5	1	---	-2.0	----	ML, ML-CL, SW	Stable hole. Tailwater high.
1102	3.00	126	4	.045	0	----	----	Unstable hole. Sloughing. See Illinois
1103	1.50	28	---	---	0	----	SM, SC	Sand scoured to limestone. comments
1104	----	--	---	---	----	----	----	Picture only. Riprap moved. in text.
1201	2.00	-- o	---	.056	-0.68	----	CL	Low stage port flow only. See Austin's comments
1202	3.00	220 o	---	.060	-1.29	----	----	Low stage port flow only. in text.
1203	2.50	90	0.2	---	-0.8	----	SM, GC	---- To be riprapped
1204	4x4	--	---	.030	-2.0	----	Shale	Part full flow. for 30 ft.
1301	3.50	170	---	---	-2.4	0.25	SM	High tailwater.
1302	2.00	49	---	---	-0.1	0.02	CL, loess	Stable hole.
1303	3.50	250	---	---	+0.2	0.02	CL	Stable hole.
1304	3.00	165-195	4-6[6]	---	-1.0	0.02	CL	Rocky soil.
1305	8x8	--	---	---	-1.0	0.02	CL, loess	No discharge given. Designed for part full flow.
1306	3.50	--	6-8[6]	---	-2.5	0.02	CL	No discharge given.
1401	2.50[3]	30	---	0	0	0.01	CL, loess	Stable hole.
1402	2.00	28	---	0	0	0.02	CL, loess	Stable hole.
1403	2.50[3]	46	5[6]	0	0	0.01	----	Stable hole.
1404	3.50[4]	224	---	0	-1.71	----	SM, ledge right	Stable hole. Rock ledge on left, sand strata on right.
1501	----	35 p	---	---	----	0.25	SM, SP	Scour during construction. Built riprapped plunge pool.
1601	1.50	24	21	.040	-3.5	----	CL, PI=10-22	High tailwater.
2201	3.00	175 d	---	---	-3.0	0.1	SM	Upstream end of enlarged hole riprapped.
2202	3.00	183 d	---	.027	0	----	SP	Upstream end of hole riprapped 3 years after construction.
2203	1.67	46 d	---	---	+2.0	0.2	SP, SM, loess	Completely riprapped.
2204	1.50	36 d	---	---	+1.0	0.04	ML	Excessive scour. Will be repaired.
2205	1.67	43 d	---	.020	+0.3	0.35	SP, SM	Excessive scour. Contract to enlarge and riprap.
2206	1.50	35.5 d	---	----	+0.9	0.25	SP, loess	Excessive scour. Contract to repair.
2207	2.00	45 a	---	.036	-0.5	0.25	SM	Nearly stable.
2208	2.00	63 a	---	.052	-1.5	0.015	CL, loess	High tailwater. Grass one side, black locust other side.
2209	2.00	22 d	---	.036	-2.0	0.002	MH, clay	High tailwater. Stable.
2210	2.00	65. a	---	.104	+1.0	0.06	CL, ML	Nearly stable.
2211	2.00	52 a	---	.042	-1.3	0.03	ML	Stable. High tailwater. Beaver dam.
2212	3.50	180 a	30 ±	----	+1.0	----	SM, loess	Riprap planned. Over winter, 6 or 7 full flows, 3-7 days each.
2213	2.50	--	---	----	-1.0	0.25	sand, gravel, loess	Large hole.
2301	2.00	60	---	.010	+0.12	0.7	GC, limestone	On rock with large gravel.
2302	2.00	50	---	.010	+0.5	0.02	GW, limestone	Well graded limestone gravel of several pounds. Rock slabs.
2303	3.00	150	---	.010	-0.08	0.01	CL, shale	Soft clay and shale; erosive material.
2304	3.50	92	---	.010	0	0.02	CL, shale	Holes stable. No excessive scour. At least 5 flows.
2305 2@	2.50	2@80	---	.010	-0.14	0.01	soft clay, shale	Eroded to shale. Two pipes.
2306	3.00	109	---	.008	-3.65	0.02	ML, sandstone	Scour in fill and sandstone. Outlet submerged. Slug flow. Water thrown 20 ft in air.
3101	1.25	--	---	----	+1.5	0.02	ML	No flow history. Poor scour map.
3102	2.00	67	3.5	----	----	0.1	SC	Discharge-time curve in report. Poor scour map.
3103	----	--	---	----	----	0.2	SM	No flow history. Poor scour map.
3104	1.50	--	---	----	-1.0	0.2	SM	No flow history.
3105	1.25	15	---	----	+2.2	0.2	SP, SM	Data from letter.
3301 2@	3.50	2@159	---	.010	-1.67	0.06	CL, ML	Poor flow history. Inlet changed by tenant.
3302	2.00	27	---	.010	0	0.03	SC, SM	Full flow 5 times.
3303	2.50	63	---	.010	+0.2	0.02	SC, SM	----
3304 2@	3.50	2@56.5	---	----	+2.5	0.03	SP, GP	No full flow.
3401	1.75	47.4	---	.06	+1.7	0.01	SM, CL	No flow history. Priming discharge.
3402	1.50	26 o	---	.04	-1.0	0.1	SM	Seepage. 13-in orifice, 18-in pipe.
3403	1.50	13 o	---	.10	+2.0	0.03	CL	Seepage. Beach left. 13-in orifice, 18-in pipe.
3404	3.00	27	---	----	+0.1	0.04-0.15	ML, SM	No full flow. Two ports 8 x 28 in. One storm caused scour.
3405	2.00	37.4	8	.05	-0.2	0.06	CL, SC, PI=11	Priming discharge. Erodible bottom, stable upper horizon. Sand boils.
3406	2.50	126	---	.034	-0.3	0.1	SM-SC, CL, PI=7	Priming discharge. Low cohesive bottom. Vertical bank.
3407	2.50	85.7	---	.02	-1.2	0.003	CH	Priming discharge. No flow history.
3408	2.50	114	10	.045	-1.1	0.3	SM, SC	Stable hole. Erodible material at right bank base.
3409	2.00	69.7	28	.035	+1.8	0.05	CL, PI=13	Erosive material left, siltstone gravel right.
3410	3.00	70.8	34	.02	-0.78	0.1	SC, CL-GC, PI=16	Stable hole. Priming discharge.
3411	3.00	121.9	---	.07	-1.5	0.07-0.09	CL, SM, PI=12	Excessive scour. Noncohesive soil. Priming discharge.

Table 1.—Summary of SCS Scour Hole Data—Continued

Hole number[1]	D feet	Q cfs	Time[2] days	S	Z_p feet	d_{50} mm	Unified Soil Classification	Notes
3412	3.00	194.4	---	.04	-2.7	Riprap	ML, SM	High tailwater. Riprap repair.
3413	3.00	183.8	---	.03	0	0.1	ML, SM	Riprap repair.
3414	3.00	48.0	---	.021	-3.8	0.03	SM	High tailwater.
3415	2.50	72.7	---	.019	+5.7	----	CL, PI=12	Riprap repair, bent undermined.
3416	2.00	64.5	---	----	+2.1	Riprap	----	Riprap repair, bent undermined.
4001	3.00	153	---	----	-2.0	0.01-0.02	CL, ML, PI=7-11	High tailwater.
4002	1.50	25	---	----	0	0.02-0.3	CL, SM, PI=10	Silty sand loess soil.
4003	2.00	47	---	----	-1.5	0.03-0.2	CL-ML, SM	Silty sand loess soil. Downstream channel degraded.
4004	1.50	25.5	---	----	+3.0	0.02-0.3	CL-ML, SM	Silty sand loess soil. Downstream channel degraded.
4005	2.00	44	---	----	-0.90	0.05	CL	Clay.
4006	1.67	39	---	----	+0.5	0.01-0.07	CL, CL-SC, PI=10-16	----
4007	1.25	17	---	----	-0.5	0.02	CL	----
4008	2.00	42	---	----	+1.0	0.02	CL, PI=10	----
4009	2.00	42	---	----	+2.0	0.05	CL-ML	----
4010	1.50	30	---	----	+0.5	0.01	CL, ML	----
4011	1.50	25	---	----	+1.0	0.03	CL, ML	----
4012	2.00	50	---	----	0	0.07	ML	Downstream degradation. Widest of holes studied.
4013	2.00	50	---	----	-1.0	0.02	CL, PI=10	High tailwater.
4014	3.00	140	---	----	+2.0	0.02	CL-ML, PI=6	Downstream degradation. Widest of holes studied.
4015	3.00	93	---	----	+2.0	----	----	Excavated stilling basin.
4101	4.50	355	---	----	----	----	----	Riprap repair. Photo shows riprap scour.
4102	4.00	--	---	----	----	----	CL	Riprap repair.
4103	4.75	--	---	----	----	----	SM	Riprap repair.
4701	6x6	1080	---	----	----	0.2	SP	Riprap plunge pool.
4702	3.50	--	---	----	-1.6	0.2	SP, gravel 2-12"	----
4703	3.00	180	---	----	-1.2	0.2	GM	----
4704	3.50	298	---	.01	0	0.7-3	GM	----
4705	2.50	95	---	.01	-2.0	0.7	GM, GP	Gravel bed.
4706	2.50	100	---	.01	-1.5	3	GM	Gravel bed.
4707	----	325	---	----	-2.4	0.2	GM	Gravel bed.

[1]First 2 digits: State number in alphabetical order; last 2 digits: number of scour hole. [2]Length of time of scour. [3]24-in barrel, 30-in cantilever. [4]36-in barrel, 42-in cantilever. [5]Silted in 3.5 ft, A_m/D = 1.17. [6]Number of times. [a]Actual discharge computed. [d]Design discharge. [o]Orifice-controlled discharge. [p]Priming discharge.

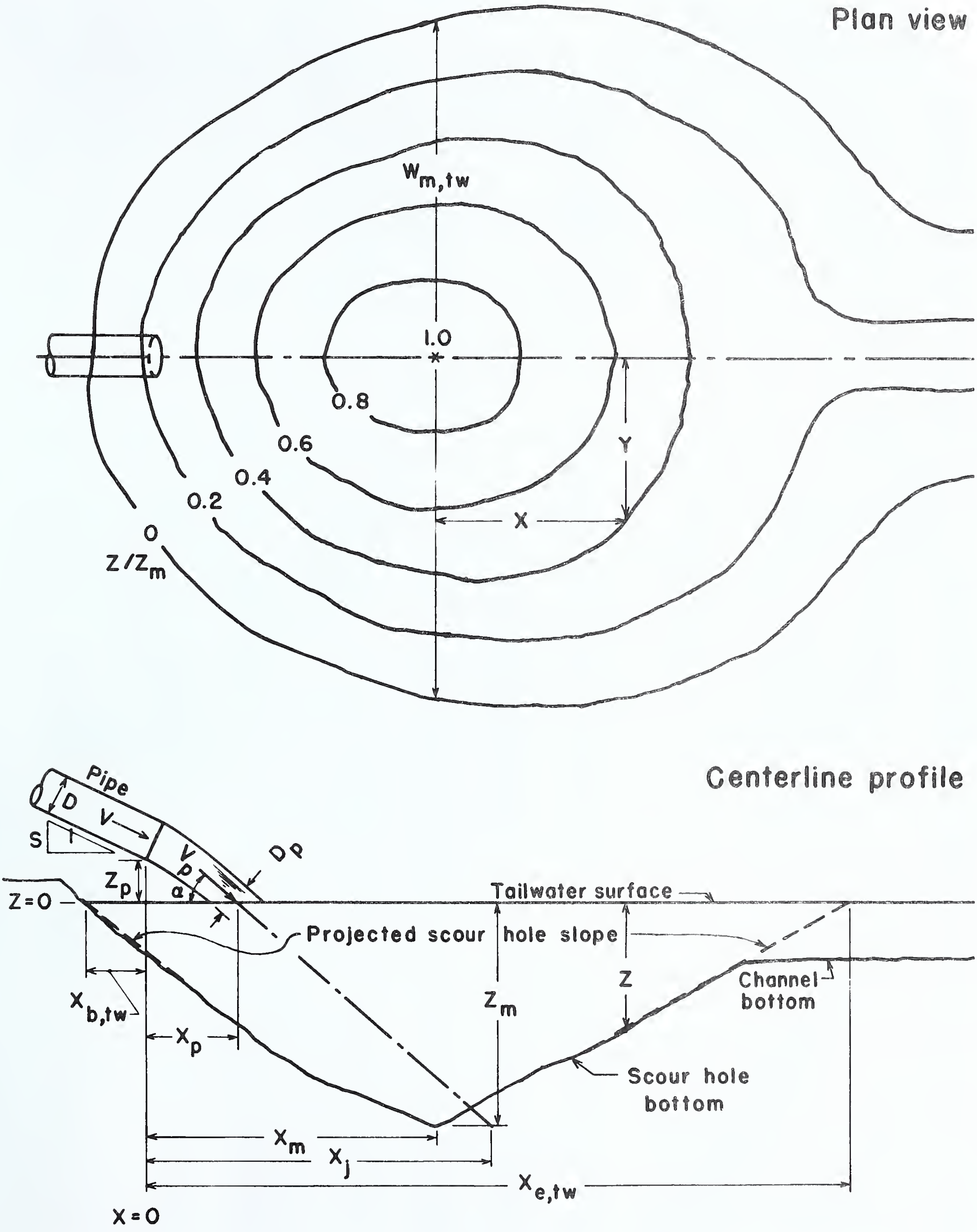

Figure 1.—Scour hole dimensions.

Table 2.—Summary of SCS Scour Hole Dimensions and Computations

Hole number[1]	$Q/\sqrt{gD^5}$	Z_p/D	Z_m feet	Z_m/D	X_m feet	X_m/D	X_m/X_j	$d_{50}/D \times 10^3$	F_d	$\frac{X_m-X_{b,tw}}{Z_m}$	$\frac{X_{e,tw}-X_m}{Z_m}$	$W_{m,tw}/2$—feet Left	$W_{m,tw}/2$—feet Right	$\frac{W_{m,tw}}{2Z_m}$
0101	1.56	+0.75	5.2	2.60	13.0	6.50	1.20	0.312-0.230	116-135	4.81	6.54	26.5	17.0	4.18
0301	1.94	-0.82	5.0	2.73	10.0	5.46	2.03	----	Riprap	----	-----	----	----	----
0901	1.56	-0.20	4.0	2.00	22.0	11.00	2.22	0.164	160	5.75	6.88	11.2	15.2	3.38
0902	1.75	-0.08	3.9	1.56	20.0	8.00	1.57	0.262	136	5.38	12.82	13.7	17.0	3.94
0903	2.94	+0.20	2.7	1.80	0.0	0.0	0	0.087-0.875	343-109	1.11	18.52	16.0	15.5	5.83
0904	0.25 o	+1.19	5.7	2.84	10.0	5.00	4.67	0.164-0.328	113-80	2.02	7.02	13	11	2.11
0905	1.59	+0.45	8.6	4.30	12.0-32.0	6.00-16.00	0.89-2.36	0.656	81	1.51-3.84	6.05-3.72	20	26	2.67
0906	1.34	+0.08	10.2	4.08	12.5	5.00	1.07	0.656	148-104	2.16	5.78	30	22	2.55
0907	1.31	+1.06	8.0	4.57	19.9	11.37	1.87	0.375-1.125	98-56	2.94	3.44	29	17	2.88
0908	0.40 o	-0.23	4.9	1.40	50.0	14.29	11.19	0.047	205	11.22	22.45	34.5	40	7.60
0909	0.45 o	+0.40	10.2	4.08	20.0	8.00	3.52	0.394	72	2.94	4.80	36	28	3.14
0910	1.67	+0.60	6.5	3.90	15.0-20.0	9.00-12.00	1.34-1.79	0.394	107	2.62-3.38	4.62-3.85	26	26	4.00
0911	1.67	+1.02	7.4	4.44	16.0	9.60	1.35	0.098	216	2.70	4.59	18	29	3.18
0912	1.56	+0.90	9.0	4.50	2.0	1.00	0.15	0.656	80	0.89	7.78	37.5	20	3.19
0913	1.56	-1.25	6.9	3.45	14.0	7.00	1.16	----	---	3.91	7.10	12	19	2.25
0914	1.18	+0.20	11.1	4.44	18.0	7.20	1.31	----	---	1.98	3.51	19	22	1.85
1101	2.07	+1.00	6.8	3.40	36.0	18.00	2.43	----	---	8.24	8.82	13.5	14.5	2.06
1102	1.43	0.00	12.8	4.27	31.0	10.33	1.70	----	---	3.13	3.52	28	31	2.30
1103	1.79	0.00	5.3	3.53	17.0	11.33	1.68	----	---	4.15	5.66	20	32	4.91
1104	----	-----	----	----	----	-----	-----	----	---	----	----	---	---	----
1201	---- o	-0.34	3.8	1.90	10.0	5.00	-----	----	---	4.21	6.58	10.5	15	3.36
1202	2.49 o	-0.43	4.4	1.47	20.0	6.67	1.08	----	---	8.64	6.82	43	20	7.16
1203	1.61	-0.32	5.6	2.24	10.0	4.00	0.76	----	---	4.46	11.96	10.5	12.5	2.05
1204	---	-0.44	14.0	3.10	30.0	6.65	-----	----	---	3.38	----	43	44	3.11
1301	1.31	-0.69	13.7	3.91	24.0	6.86	1.22	0.234	---	2.99	4.45	20	22	1.53
1302	1.53	-0.05	5.5	2.75	20.0	10.00	1.84	0.033	354	5.27	6.36	23	23	4.18
1303	1.92	+0.06	6.4	1.83	20.0	5.71	1.00	0.019	539	4.84	6.41	25	28	4.14
1304	1.87-2.21	-0.33	7.0[2]	2.33[2]	28.0	9.33	1.55-1.36	0.022	490	5.43	5.57	22	20	3.00
1305	----	-0.11	13.0	1.44	24.0	2.66	-----	----	---	----	----	23	50	2.81
1306	----	-0.71	12.0	3.43	28.4	8.11	-----	0.019	---	----	----	35	30	2.71
1401	0.54	0.00	7.3	2.92	10.0	4.00	1.76	0.013	400	2.74	4.11	21	27	3.29
1402	0.87	0.00	4.5	2.25	10.0	5.00	1.60	0.033	279	3.78	11.11	11	26	4.11
1403	0.82	0.00	7.1	2.84	10.0	4.00	1.22	0.013	435	2.96	2.96	17	25	2.96
1404	1.72	-0.49	6.7	1.91	25.0	7.14	1.89	----	600	17.31	15.67	---	---	----
1501	---- p	-----	----	----	----	-----	-----	----	---	----	----	---	---	----
1601	1.54	-2.33	5.8	3.87	30.0	20.0	3.26	----	---	7.07	15.34	15	15.5	2.63
2201	1.98 d	-1.00	13.2	4.40	44.0	14.67	1.83	0.109	228	4.55	9.85	35	57	3.48
2202	2.07 d	0.00	10.0	3.33	- 0.5	- 0.17	- 0.02	----	---	2.30	9.90	---	---	----
2203	2.26 d	+1.20	2.6	1.56	- 0.5	- 0.30	- 0.05	0.394	134	----	----	17	25	8.08
2204	2.30 d	+0.67	6.6	4.40	25.0	16.67	1.88	0.087	283	6.06	4.55	35	25	4.55
2205	2.11 d	+0.18	6.9	4.14	25.0	15.00	1.88	0.689	95	5.94	5.80	36	43	5.72
2206	2.27 d	+0.60	10.0	6.67	21.0	14.00	1.31	0.547	112	3.50	6.00	46.5	44	4.53
2207	1.40 a	-0.25	12.7	6.35	21.0	10.50	1.40	0.411	96	3.23	4.41	41	19	2.36
2208	1.96 a	-0.75	7.4	3.70	32.0	16.00	2.27	0.025	477	6.22	4.46	14.5	44.5	3.99
2209	0.69 d	-1.00	7.9	3.95	20.0	10.00	3.05	0.003	835	3.29	4.05	10	14	1.52
2210	2.03 a	+0.05	2.9	1.45	18.0	9.00	1.80	0.098	244	6.90	17.24	17	25	7.24
2211	1.62 a	-0.65	9.8	4.90	50.0	25.00	3.50	0.049	299	5.41	-----	20	19	1.99
2212	1.38 a	+0.29	18.0	5.14	31.0	8.86	1.32	-----	---	2.83	4.44	88	64	4.22
2213	----	-0.40	11.9	4.76	25.0	10.00	-----	0.328	---	5.29	5.63	71	75	6.13
2301	1.87	+0.06	1.8	0.90	0.0	0.00	0	1.148	8.49	8.33	-----	8	12	5.56
2302	1.56	+0.25	3.1	1.55	11.0	5.50	1.20	0.033	358	4.84	6.13	18	17	5.65
2303	1.70	-0.03	7.7	2.57	15.0	5.00	0.58	0.011	812	2.60	2.08	9	12	1.36
2304	0.71	0.00	5.0	1.43	15.0	4.29	2.70	0.019	420	4.60	7.20	19	13	3.20
2305	1.43	-0.06	4.0	1.60	25.0	10.00	2.34	0.013	540	7.75	8.25	24	16	5.00
2306	1.23	-1.22	6.9	2.30	13.0	4.33	1.02	0.022	389	4.20	6.09	13	9	1.59
3101	----	+1.20	6.6	5.28	----	-----	-----	0.052	---	----	-----	---	---	----
3102	2.09	-----	----	----	----	-----	-----	0.164	---	----	-----	---	---	----
3103	----	-----	----	----	----	-----	-----	-----	---	----	-----	---	---	----
3104	----	-0.67	8.0	5.33	22.0	14.67	-----	0.437	---	4.38	6.25	20	16	2.25
3105	1.51	+1.76	7.5	6.00	20.0	16.00	1.97	0.525	97	3.77	3.29	22	18	2.67
3301	1.22	-0.48	9.2	2.63	8.0-28.0	2.29-8.00	0.52-1.81	0.056	242	2.50-4.67	4.02-1.85	18	25	2.34
3302	0.84	0.00	1.5	0.75	7.0	3.50	1.57	0.049	226	----	-----	9	8	5.67
3303	1.12	+0.08	3.9	1.56	26.0	10.40	3.02	0.026	341	----	-----	11	10	2.69
3304	0.31	+0.71	5.4	1.54	10.0	2.86	2.79	0.028	261	2.22	2.59	21	17	3.52
3401	2.06	+0.97	8.7	4.97	21.0	12.00	1.45	0.019	565	2.41	5.29	29	30	3.39
3402	1.66 o	-0.67	4.5	3.00	2.6	1.73	0.30	0.219	144	2.67	-----	19	18	4.11
3403	0.83 o	+1.33	3.7	2.47	23.0	15.33	4.96	0.066	210	9.19	5.95	23	21	5.95
3404	0.31	+0.03	7.4	2.47	13.0	4.33	3.52	0.044-0.164	209-108	2.70	-----	16	12	1.89
3405	1.17	-0.10	5.0	2.50	11.0	5.50	1.34	0.098	179	5.20	-----	27	36	6.30
3406	2.25	-0.12	9.3	3.72	24.8	9.94	1.26	0.131	227	2.69	3.44	19	19	2.04
3407	1.53	-0.48	8.1	3.24	16.0	6.40	1.12	0.004	1023	2.59	-----	37	27	3.95
3408	2.03	-0.44	8.2	3.28	38.0	15.20	2.20	0.394	122	5.61	3.05	17(39)	39	4.76
3409	2.17	+0.90	5.8	2.90	18.0	9.00	1.29	0.082	280	3.28	5.52	38	16(38)	6.55
3410	0.80	-0.26	9.7	3.23	12.0	4.00	1.18	0.109	150	1.29	4.33	12	23	1.80
3411	1.38	-0.50	13.2	4.40	19.0	6.33	1.06	0.077-0.098	219-194	1.74	-----	18	20	1.44

Table 2.—Summary of SCS Scour Hole Dimensions and Computations—Continued

Hole number[1]	$Q/\sqrt{gD^5}$	Z_p/D	Z_m feet	Z_m/D	X_m feet	X_m/D	X_m/X_j	$d_{50}/D \times 10^3$	F_d	$\frac{X_m - X_{b,tw}}{Z_m}$	$\frac{X_{e,tw} - X_m}{Z_m}$	$W_{m,tw}/2$—feet Left	Right	$\frac{W_{m,tw}}{2Z_m}$
3412	2.20	-0.90	13.2	4.40	28.0	9.33	1.13	-----	Riprap	3.26	4.70	46	46	3.48
3413	2.08	0.00	8.4	2.80	24.0	8.00	1.19	0.109	236	3.57	-----	20	20	2.38
3414	0.54	-1.27	7.7	2.57	19.8	6.60	3.10	0.033	253	4.42	-----	33	34	4.35
3415	1.30	+2.28	7.3	2.92	30.0	12.00	2.17	-----	---	3.70	-----	21	27	3.29
3416	2.01	+1.05	5.9	2.95	24.0	12.00	1.73	-----	Riprap	4.41	-----	18	20	3.22
4001	1.73	-0.67	7.5	2.50	15.0	5.00	0.86	0.011-0.022	660-466	2.80	5.47		25	1.67
4002	1.60	0.00	3.5	2.33	23.0	15.33	2.89	0.044-0.656	315- 81	----	10.00		51	7.29
4003	1.46	+0.75	7.5	3.75	10.0-20.0	5.00-10.00	0.84-1.68	0.049-0.328	282-109	1.60-2.93	4.53-3.20		31	2.07
4004	1.63	+2.00	3.0	2.00	15.0	10.00	1.67	0.044-0.656	359- 93	----	8.33		34	5.67
4005	1.37	-0.45	5.3	2.65	42.0	21.00	4.28	0.082	211	9.06	2.83		25	2.36
4006	1.92	+0.30	2.5	1.50	7.0	4.20	0.77	0.020-0.138	526-199	----	0.40		16	3.20
4007	1.72	-0.40	2.3	1.84	44.0	35.20	6.72	0.052	300	----	0.87		21.5	4.67
4008	1.31	+0.50	2.2	1.10	6.0	3.00	0.82	0.033	327	3.64	----		18	4.09
4009	1.31	+1.00	9.5	4.75	18.0	9.00	1.46	0.082	207	2.00	1.37		34	1.79
4010	1.92	+0.33	5.9	3.93	20.0	13.33	1.79	0.022	499	----	10.17		42	3.56
4011	1.60	+0.67	6.1	4.07	30.0	20.00	3.02	0.066	257	----	1.64		28	2.30
4012	1.56	0.00	5.8	2.90	10.0	5.00	0.89	0.115	191	2.24	6.21		52	4.48
4013	1.56	-0.50	6.0	3.00	10.0	5.00	0.88	0.033	358	2.50	3.67		27	2.25
4014	1.58	+0.67	10.0	3.33	35.0	11.67	1.94	0.022	442	3.80	3.60		64	3.20
4015	1.05	+0.67	----	----	----	-----	-----	-----	---	----	----		---	----
4101	1.46	-----	----	----	----	-----	-----	-----	---	----	----	---	---	----
4102	----	-----	----	----	----	-----	-----	-----	---	----	----	---	---	----
4103	----	-----	----	----	----	-----	-----	-----	---	----	----	---	---	----
4701	1.60	-----	----	----	----	-----	-----	0.187	---	----	----	---	---	----
4702	----	-0.46	9.6	2.74	17.0	4.86	-----	-----	---	2.71	3.23	13.8	16.0	1.55
4703	2.04	-0.40	11.2	3.73	20.0	6.67	0.88	0.219	164	2.95	2.41	31	24	2.46
4704	2.29	0.00	9.1	2.60	23.0	6.57	0.91	0.656-2.812	103- 50	3.63	3.30	22.5	21.5	2.42
4705	1.69	-0.80	7.6	3.04	15.0	6.00	0.99	0.919	71	4.21	5.92	35	27	4.08
4706	1.78	-0.60	8.3	3.32	16.0	6.40	0.98	3.937	35	3.73	4.46	24.5	22	2.80
4707	----	-----	----	----	----	-----	-----	-----	---	----	----	28	28	----

[1] First 2 digits: State number in alphabetical order; last 2 digits: number of scour hole. [2] Silted in 3.5 ft, $Z_m/D = 1.17$. [a] Actual discharge computed. [d] Design discharge. [o] Orifice-controlled discharge. [p] Priming discharge.

1 First two digits: State number in alpabetical order; last two digits: number of scour hole.
2 Silted in 3.5 feet, $Z_m/D = 1.17$
a Actual discharge computed.
d Design discharge.
o Orifice-controlled discharge.
p Priming discharge.

The third step in the analysis was to plot the data. Lines are drawn between some of the plotted points to indicate a range of values (figs. 2 to 7). For the densimetric Froude number, the line extremities mainly indicate a range of bed material sizes. For discharges, the range may be from the priming discharge to the maximum discharge—a range through which the flow may pass during both rising and falling stages of the runoff hydrograph. For distances, the scour hole may have a flat bottom or the dimension may vary for some other reason.

Results of Analysis

Six plots of data will be presented as follows:

1. Figure 2, the relative size of bed material $\mathbf{d}_{50}/\mathbf{D}$ vs. the dimensionless discharge $\mathbf{Q}/(\mathbf{g}\mathbf{D}^5)^{1/2}$,
2. Figure 3, the relative maximum scour depth $\mathbf{Z}_m/\mathbf{D}$ vs. the densimetric Froude number $\mathbf{F}_d$,
3. Figure 4, the distance from the cantilever pipe exit to the maximum depth of scour $\mathbf{X}_m$ divided by the computed distance from the cantilever pipe exit to the point at which the jet impinges on the maximum scour depth elevation $\mathbf{X}_i$, $\mathbf{X}_m/\mathbf{X}_i$, vs. the dimensionless discharge $\mathbf{Q}/(\mathbf{g}\mathbf{D}^5)^{1/2}$, and in terms of maximum scour depth $\mathbf{Z}_m$, the scour hole axis coordinates,
4. Figure 5, $(\mathbf{X}_m - \mathbf{X}_{b,tw})/\mathbf{Z}_m$,
5. Figure 6, $(\mathbf{X}_{e,tw} - \mathbf{X}_m)/\mathbf{Z}_m$,
6. Figure 7, $\mathbf{W}_{m,tw}/2\mathbf{Z}_m$ vs. the dimensionless discharge $\mathbf{Q}/(\mathbf{g}\mathbf{D}^5)^{1/2}$.

Data in these plots define the scour hole form and evaluate and locate the maximum scour depth and the length and width of the scour hole at the tailwater elevation. The data available for this analysis are insufficient to further define the shape of the scour hole. Based on laboratory tests, we suggest that elliptical contours be fitted to the axes determined from the plots and that the scour hole be shaped as an elliptical cone or truncated elliptical cone (flat scour hole bottom).

Beaching

During laboratory tests of the scour at cantilevered pipe outlets, we found that the scour hole had the shape of an inverted cone if the discharge was low or the bed material was large. If certain limits were exceeded, however, the top of the scour hole widened and "beaches" formed along the periphery. Flow was upstream along the beaches. This condition has been observed in the field.

To see if the field data agreed with the laboratory findings, we inspected all SCS scour hole maps and photographs to determine the occurrence or absence of beaching. The results of this inspection are plotted in figure 2. The solid diamonds indicate definite beaching with scour patterns similar to those observed during the laboratory tests. The open diamonds indicate probable beaching, but the evidence of beaching often was slight or suggestive only. The circles indicate no evidence of beaching. Many of the latter holes had vertical banks above the water line.

Because the circles and diamonds are randomly distributed in figure 2, no pattern is evident. This finding differs from that obtained from the laboratory tests, where the limit between the desirable conical scour hole and the undesirable beached scour hole was well defined.

Although disappointing, this finding is perhaps not surprising. There are considerable differences between some of the laboratory and field conditions. For example:

1. Orifices controlled the flow in the field, in some cases, and the pipe, computed as if full, probably was only partly full when $\mathbf{Q}/(\mathbf{g}\mathbf{D}^5)^{1/2}$ was less than about 0.5;
2. The flow period in the field was probably insufficient to produce beaching in many cases, whereas the full flow period in the laboratory was relatively long;
3. Noncohesive, uniform-sized bed material was used in the laboratory, whereas in the field the bed material was usually fine and cohesive;
4. The laboratory-beaching limit is based on values of $\mathbf{d}_{50}/\mathbf{D}$ from 0.018 to 0.301, whereas only in three instances did the field value exceed 0.001.

Maximum Scour Depth

The maximum depth of scour in terms of the pipe diameter $\mathbf{Z}_m/\mathbf{D}$ is plotted in figure 3 against the densimetric Froude number $\mathbf{F}_d$. The densimetric Froude number is comprised of the jet plunge velocity—a measure of the scouring force—and the relative sediment density and size—a measure of the resistance to scour. The densimetric Froude number increases with increasing plunge velocity and decreases with increasing bed material density and size. Most of the variation in $\mathbf{F}_d$ in figure 3 is attributable to bed material size.

Figure 3 shows considerable scatter of the data; however, the maximum depth of scour seems to be independent of the densimetric Froude number. This is in contrast to laboratory tests with uniform-sized sands ranging from 0.5 to 8 mm, where the maximum scour depth varied from 2 to 14 pipe diameters over a densimetric Froude number range of 3 to 14—large depths and a small range compared with the field values. The deepest laboratory holes, however, occurred for pipe heights of $2 \leqq \mathbf{Z}_p/\mathbf{D} \leqq 8$—a range beyond that of the SCS field data. For laboratory pipe heights in the range of the field data, only a few scour depths exceeded 7**D**. Another consideration is that the laboratory measurements of scour are based on ultimate scour hole depths, whereas most field scour holes probably had not reached their ultimate depth. Nevertheless, the field and laboratory findings are in reasonable agreement.

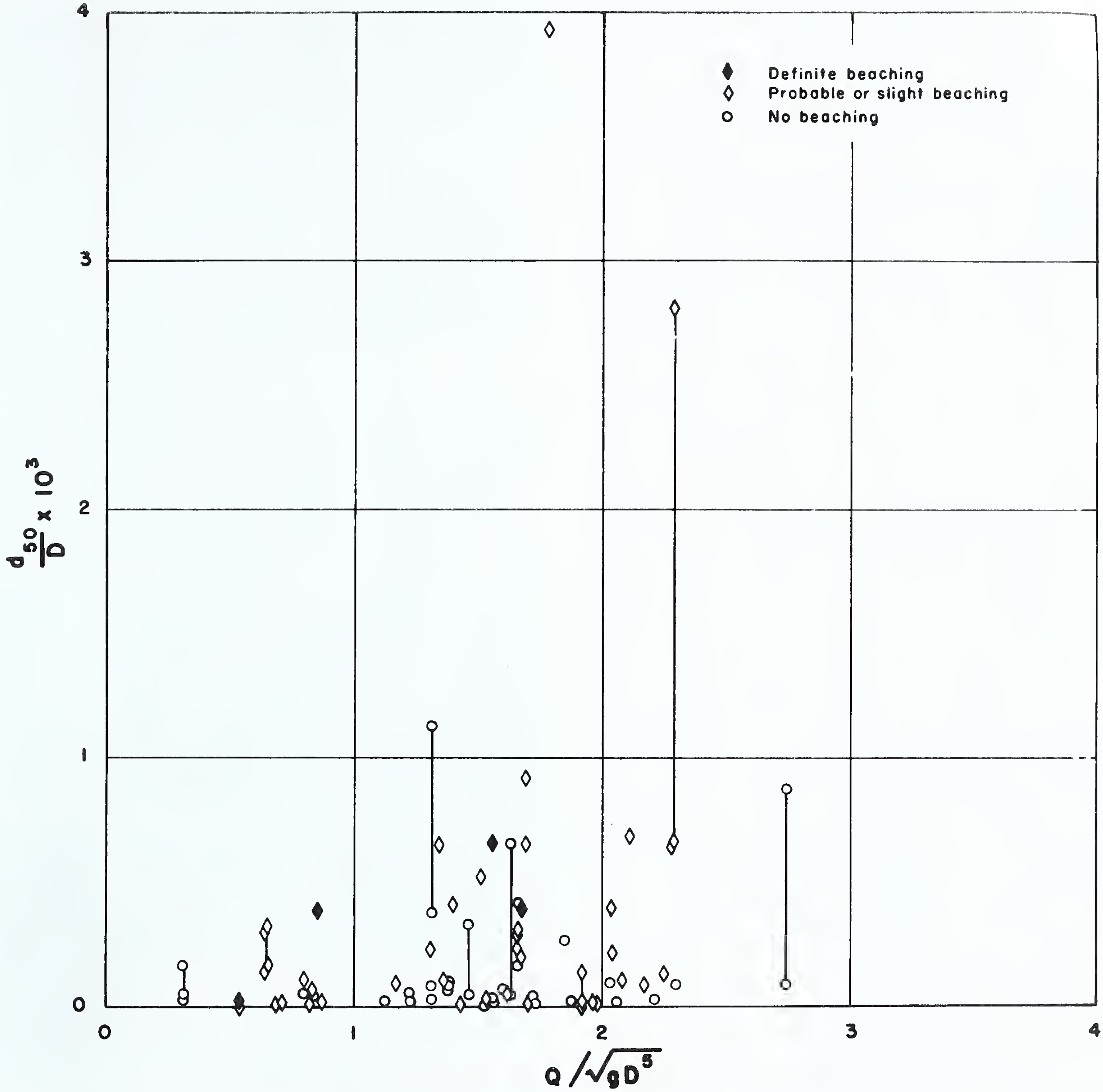

Figure 2.—Ratio of bed material median diameter to pipe diameter vs. dimensionless discharge.

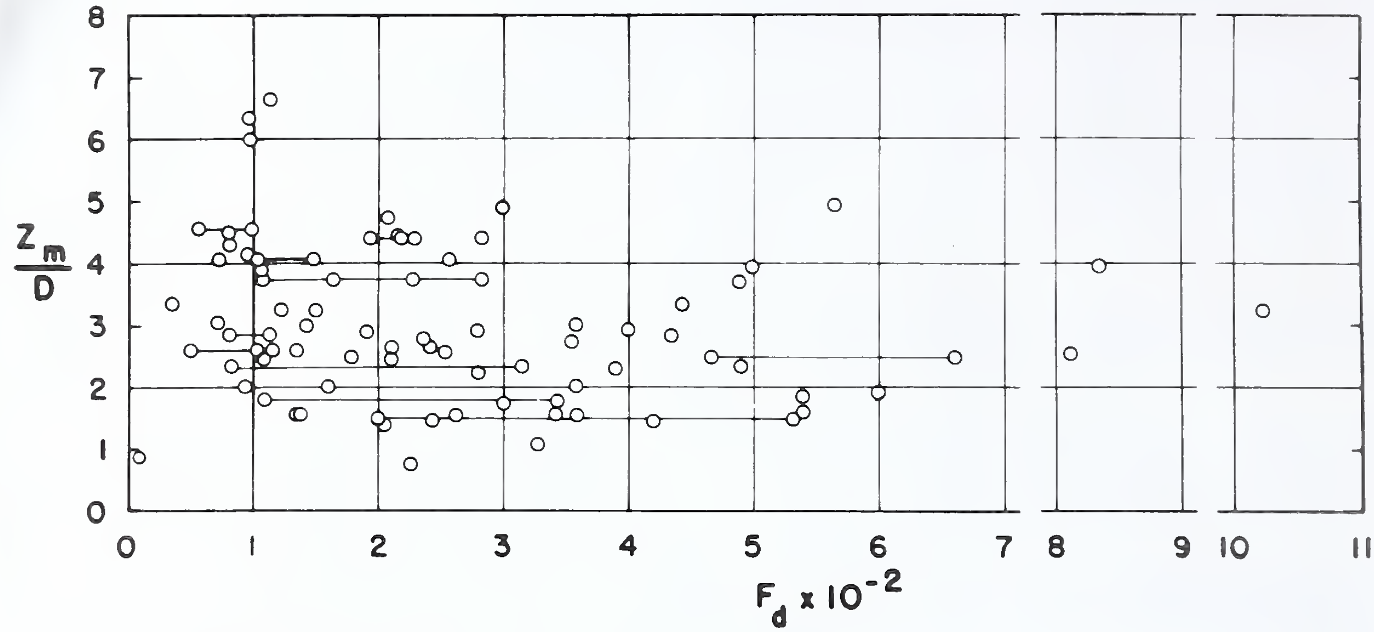

Figure 3.—Ratio of maximum scour depth to pipe diameter vs. densimetric Froude number.

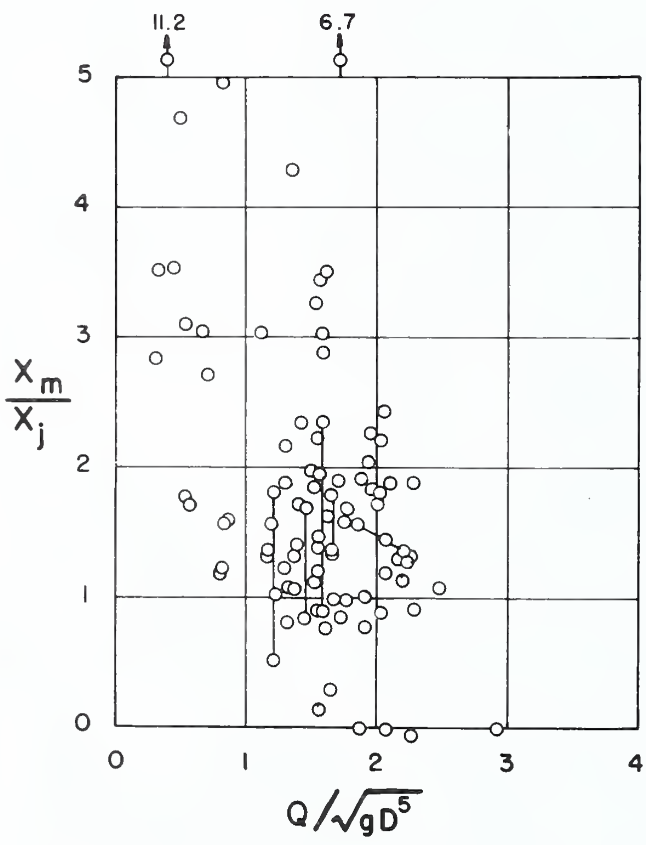

Figure 4.—Ratio of distance to maximum depth of scour to distance at which jet impinges on maximum scour depth elevation vs. dimensionless discharge.

The maximum depth of scour below the tailwater level can be expected to reach 5 pipe diameters, although three scour holes in 0.2 mm Uniform Soil Classification SM and SP soils reached or exceeded 6 pipe diameters.

Of interest is a comparison with a September 9, 1962, unpublished recommendation by M. M. Culp, retired Chief, design branch, SCS, for an excavated cantilever outlet scour hole in earth. Culp recommended a depth of 6 pipe diameters below the pipe invert or about 5 pipe diameters below the tailwater level. Culp further recommend that the excavation be lined with riprap, if available, for SP, SW, SM, ML, and low CL soils. These are the soils for which data are plotted in figure 3.

R. C. Bintzler, assistant State conservation engineer in Wisconsin, in a May 23, 1969, letter and sketch to the author stated that the excavated cantilever outlet stilling basin used in Wisconsin, which was developed from experience and found to be adequate, had a depth of 2.5 to 2.8 pipe diameters. These depths fall in the average range of values plotted in figure 3 and are for GM soils.

Distance to Maximum Scour Depth
The horizontal distance from the cantilever pipe exit to the observed maximum depth of scour X_m is divided by the distance from the cantilever pipe exit to the computed point where the jet centerline strikes the elevation of the scour hole maximum depth X_j. The jet follows a projectile trajectory from the pipe exit to the

point where it enters the tailwater surface. Below the tailwater surface, the jet travels tangent to the slope at which it enters the tailwater. The ratio X_m/X_j = 1 if the maximum depth of the scour hole is located at the point where the calculated jet impinges on the elevation of the maximum depth.

The X_m/X_j data are plotted in figure 4 against the nondimensional discharge. The considerable scatter shown here was expected for field data. The average value of X_m/X_j is about 1.8 for all data; however, the data mass is below $X_m/X_j = 2.5$, and the average value is 1.3. This latter value should be satisfactory for locating the distance to the maximum scour depth and the center of the scour hole. The laboratory studies show that X_m/X_j averages 1.2.

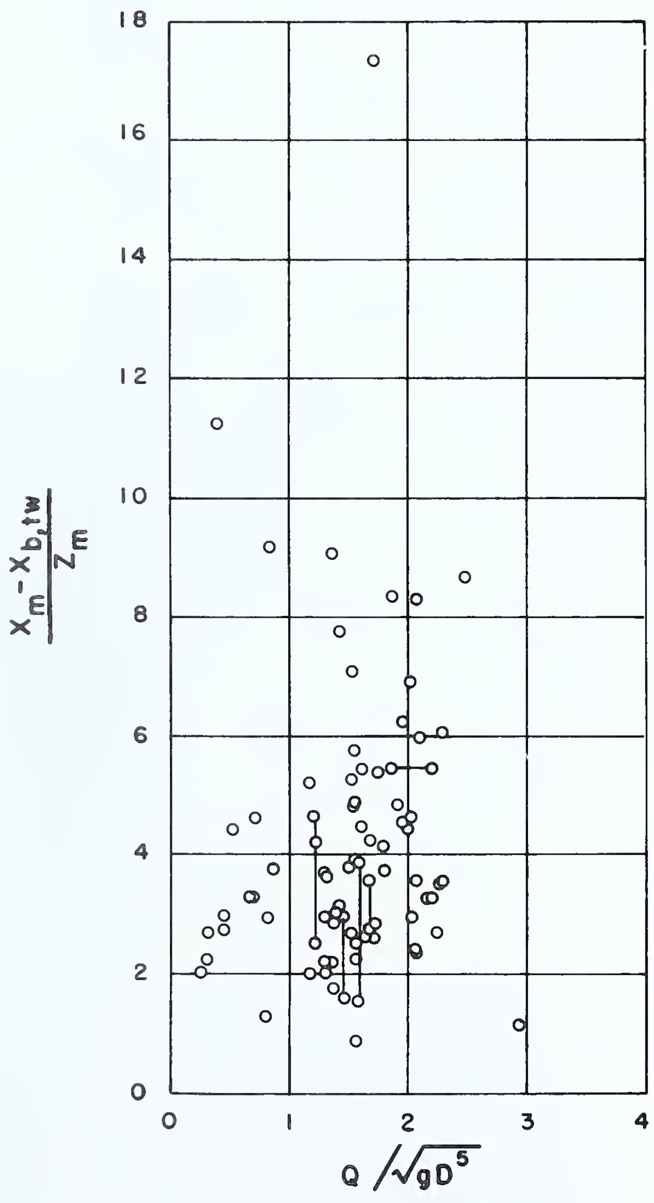

Figure 5.—Ratio of scour hole upstream axis coordinate to maximum scour depth vs. dimensionless discharge.

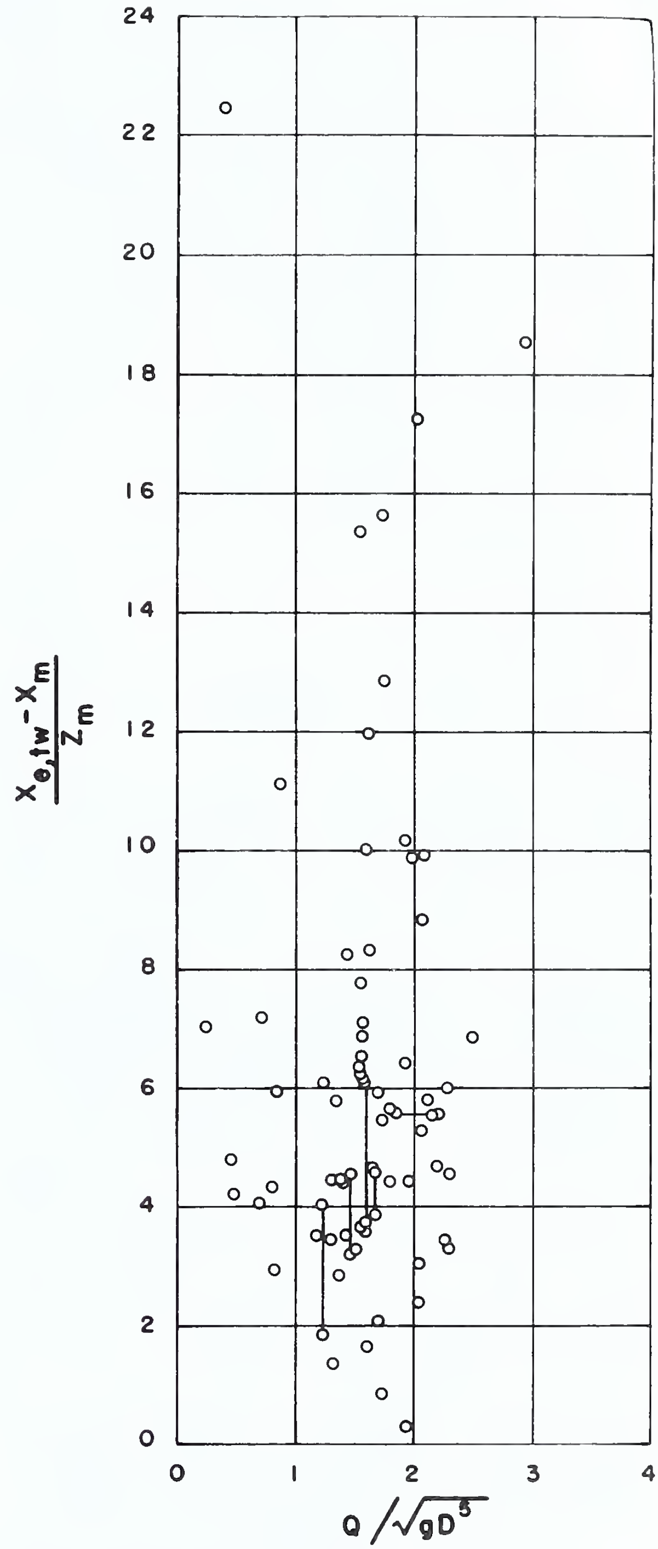

Figure 6.—Ratio of scour hole downstream axis coordinate to maximum scour depth vs. dimensionless discharge.

Distance to Ends of Scour

The distance from the cantilever pipe exit to the points where the projected slopes of the scour hole intersect the tailwater surface are $X_{b,tw}$ for the upstream end and $X_{e,tw}$ for the downstream end. In this analysis, the ends

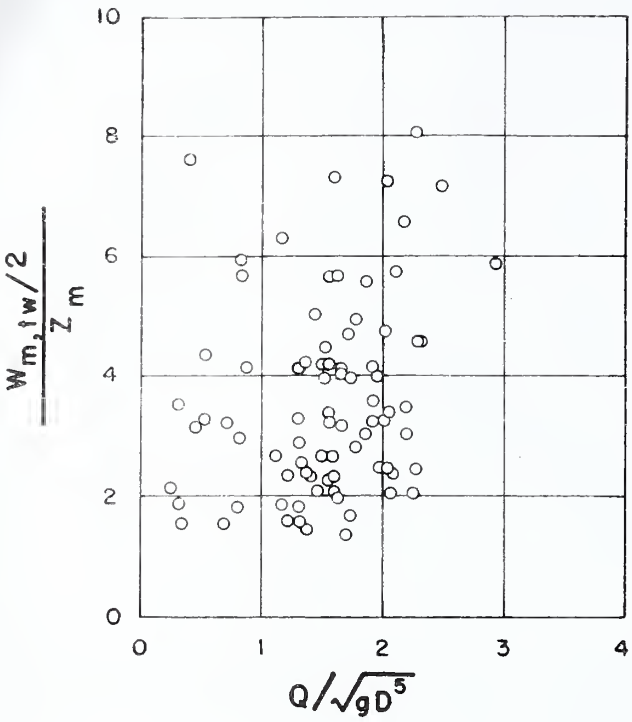

Figure 7.—Ratio of scour hole width axis coordinate to maximum scour depth vs. dimensionless discharge.

of the scour hole are measured from the point of deepest scour X_m. The distance parameters are then $(X_m - X_{b,tw})$ and $(X_{e,tw} - X_m)$ for the downstream end. These parameters are made nondimensional with Z_m. The ratios, then, are the slopes of the ends of the scour hole.

If there is a trend to the data plotted in figures 5 and 6, it is hidden in the scatter of the plotted points. Values of $(X_m - X_{b,tw})/Z_m$ and $(X_{e,tw} - X_m)/Z_m$ equal to 6 cover most of the data, and their sum can be taken as the length of the scour hole at the tailwater elevation. The total length of the scour hole would then be $12Z_m$.

Culp's recommended length is 23**D** or $4.6Z_m$, and Bintzler's length is $6.9Z_m$ to $8.0Z_m$. These lengths are only 38 to 67 percent of the observed lengths, and the end slopes, 2:1, are three times the 6:1 slopes that cover most of the observed data.

Results from the laboratory studies were different both in trend and in magnitude. The laboratory scour hole dimensions increased with $Q/(gD^5)^{1/2}$, and the magnitude of the length ratios varied in the range 1.5 to 2.5—close to the minimum lengths observed in the field.

Scour Hole Width

The procedure used to analyze the scour hole width was the same as that used for the length. The half-width of the scour hole is $W_{m,tw}/2$; the nondimensional parameter is $W_{m,tw}/2Z_m$. The data are plotted in figure 7.

Again, there is considerable scatter of the data with no apparent trend to the plotted points and the envelope value of $W_{m,tw}/2Z_m \cong 6$. A general statement is that the scour hole, because it has the same length and width, is circular.

Because Culp's excavated scour hole is a truncated cone, its width and length dimensions are identical and are 38 percent of the observed approximate envelope width of figure 7. The width of Bintzler's hole is about $5Z_m$, 42 percent of the observed approximate envelope width.

The laboratory data on the scour hole width increase with $Q/(gD^5)^{1/2}$, the range being about 1.5 to 2.1—again, close to the minimum widths observed in the field.

Soil Conservation Service Comments

The comments received from Illinois, Indiana, North Carolina, and Tennessee from the 1962 SCS study are discussed in this section against the background of the present analysis.[2]

The Illinois report included three comments:

1. Certainly duration of flow is important. Use of floodwater-retarding dams means that near-capacity, maximum-design flows occur frequently and persist for long periods. This severely tests stilling basins and causes scour holes to develop to nearly their maximum size soon after the dam is completed. Because the scouring forces are such that the scour hole develops rapidly at first and then more slowly, even short scour periods can develop large scour holes. The scour depth is approximately proportional to the logarithm of the length of time from the beginning of scour.
2. A penciled comment by an unknown reviewer is pertinent regarding the statement, "The slope of the outlet channel is significant." The comment reads: "Is it the slope or tailwater elevation with respect to the outlet that is significant?" The tailwater elevation is the important quantity. A low tailwater lets the jet drop into the scour hole at a steep angle. This results in more vertical and less horizontal energy dissipation. Even so, the horizontal component of the jet velocity may cause eddy currents that, if strong enough, will cause lateral scour.
3. On the effect of an underlying impermeable layer, only three scour holes had ledge bottoms: One was extremely long (33**D**), another a little long (16**D**), and the third had a length within the range of other holes (10**D**); only one width exceeded 6**D**, reaching 7.6**D**. The information available relative to this comment is meager and inconclusive.

[2] See Soil Conservation Service Field Data, p. 1.

From Indiana, R. H. Austin had the following comments:

1. On the depth and texture of the soil, analysis of the data indicated that little or no damage occurs in soils that have a deep uniform texture. Scour holes in such soils should develop typically.
2. On the effect of a consolidated layer on the scour, Austin suggested that the depth of the scour hole is about 4 pipe diameters. This depth agrees remarkably well with the maximum depths plotted in figure 3. The suggestion of an excavated scour hole is equivalent to the excavation of the plunge pool energy dissipator considered to be good current practice.
3. A scour hole was suggested to be excavated into the consolidated material. This comment is a logical extension of the plunge pool idea mentioned in (2) above.
4. On the dimensions of the bottom of the scour hole, information is unavailable in the data analyzed to indicate that the plunge pool should have a flat bottom. In fact, most of the scour hole longitudinal and cross section profiles did not indicate flat bottoms.
5. The data of figure 4 suggest that the jet impinges at $1.3X_t$ rather than at $1.0X_t$.
6. On the effect of high tailwater, field data does not show that high tailwater causes excessive erosion. The laboratory tests, however, show that high tailwater causes lateral eddies and erosion.

In North Carolina, the State conservation engineer and others concluded:

1. The bottom width should be 20 ft. The present analysis does not support the comment that the bottom should have a width, but the greater width should not be harmful.
2. The side slopes should be 3:1 or 4:1. Figures 5, 6, and 7 show that these side slopes are about average for the data analyzed when the bottom has no width. Side slopes of 6:1 envelope most of the data.
3. The basin length should be 30 ft for pipes less than 30 in in diameter [length, 12 pipe diameters] and probably a minimum of 50 ft for larger pipes [length, 20 pipe diameters]. Figures 5 and 6 show that the maximum scour hole length for most of the data analyzed is 12 times the maximum scour depth.

The outlet channel grade and swirling comments are similar to those made under Illinois, item (2), page 1.

From Tennessee, Bratcher concluded: The limiting scour depth and the volume of the scour hole are functions of the following:

1. Discharge.
2. Total head.

   For free flow, such as existed for the Veronese equation[1] mentioned by Bratcher, these two items affect the scour. For closed conduits, these two items are interrelated and can be combined into a single dimensionless flow parameter as has been done in the present analysis.
3. Soil properties.

   An attempt was made to discover regions of similar soil classification in figure 3. The scatter was such that no satisfactory separation was possible. Another attempt was made to develop a relationship between the plasticity index (PI) and scour depth Z_m/D. For most data the PI was zero, so no relationship could be developed. Where the PI exceeded zero, no relationship was discernible. We concluded that the relationship discovered by Bratcher is probably fortuitous.

From the comments received from the four States, it is apparent that there is, in the field, a good understanding of cantilever outlet scour holes, both qualitatively and quantitatively. Field experience has developed the criteria necessary to determine the size and location of pre-excavated basins, so plunge pool energy dissipators can be properly constructed and scour holes eliminated.

Summary

In response to SCS Advisory Notice W-705, dated September 10, 1962, field surveys were made of cantilever outlet scour holes. Analyses of these data show that:

1. The maximum depth of scour Z_m in terms of the pipe diameter D is $Z_m/D \cong 5$;
2. The average distance from the pipe exit to the point of deepest scour X_m—the center of the scour hole—in terms of the free-falling and submerged jet trajectory length X_t is $X_m/X_t \cong 1.3$;
3. The distance from the center of the scour hole to the tailwater surface at the upstream end of the scour hole $(X_m - X_{b,tw})$, the downstream end of the scour hole $(X_{e,tw} - X_m)$, and the sides of the scour hole $(W_{m,tw}/2)$ in terms of the maximum depth Z_m is $(X_m - X_{b,tw})/Z_m = (X_{e,tw} - X_m)/Z_m = W_{m,tw}/2Z_m = 6$;
4. The scour hole depths proposed by Culp and Bintzler agree well with the observed depths, but their proposed lengths and widths are much less and their side slopes are much steeper than were observed; and
5. Results from laboratory tests agree with field results regarding the maximum scour depth and its location but do not agree with respect to the scour hole length and width. No information is presently available to explain these differences. Constant flows, however, were used in the laboratory whereas runoff hydrographs were used in the field, and larger, uniform-sized, noncohesive bed materials were used in the laboratory whereas smaller, graded, cohesive bed materials were most common in the field.

[1] Scimemi, Ettore. Discussion of Model Study of Brown Canyon Debris Barrier. Transactions of the American Society of Civil Engineers 112:1016-1019. 1947.

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Nomenclature

- d_{50} bed material diameter of which 50 percent by weight is finer
- D cantilever outlet pipe diameter
- D diameter of the jet at the tailwater level elevation
- F densimetric Froude number
- g gravitational acceleration
- S slope of the cantilevered pipe, sine
- V velocity in the pipe
- V velocity of the jet where it plunges into the tailwater
- W maximum width of the scour hole at the tailwater elevation
- X longitudinal distance from the maximum scour depth to a point on the scour hole surface
- X distance from the cantilever pipe exit to the intersection of the projected scour hole upstream slope with the tailwater surface
- X distance from the cantilever pipe exit to the intersection of the projected scour hole downstream slope with the tailwater surface
- X_i distance from the cantilever pipe exit to the point where the jet trajectory intersects the elevation of the maximum scour depth
- X_m distance form the cantilever pipe exit to the maximum scour depth
- Y transverse distance from the cantilever pipe centerline to a point on the scour hole surface
- Z vertical distance from the tailwater surface to a point on the scour hole surface
- Z_m maximum depth of the scour hole below the tailwater surface
- Z_p vertical distance from the tailwater surface to the cantilever pipe invert
- α angle with the horizontal at which the jet enters the tailwater and continues to the bed
- ϱ density of the fluid
- ϱ_s density of the bed material